Preprint
UCRL-JC-148425

Yb Thin-Disk Laser Results

L. E. Zapata, R. A. Beach, S. Mitchell, S. A. Payne, and Captain S. Massey

This article was submitted to *Solid State and Diode Laser Technology Review 2002*, Albuquerque, New Mexico, June 3–6, 2002

May 14, 2001

U.S. Department of Energy

Lawrence
Livermore
National
Laboratory

Approved for public release; further dissemination unlimited

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

This work was performed under the auspices of the United States Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

This report has been reproduced directly from the best available copy.

Available electronically at http://www.doc.gov/bridge

Available for a processing fee to U.S. Department of Energy
And its contractors in paper from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
Telephone: (865) 576-8401
Facsimile: (865) 576-5728
E-mail: reports@adonis.osti.gov

Available for the sale to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: (800) 553-6847
Facsimile: (703) 605-6900
E-mail: orders@ntis.fedworld.gov
Online ordering: http://www.ntis.gov/ordering.htm

OR

Lawrence Livermore National Laboratory
Technical Information Department's Digital Library
http://www.llnl.gov/tid/Library.html

Yb Thin-Disk Laser Results

L. E. Zapata, R. A. Beach, S. Mitchell and S. A. Payne
University of California, Lawrence Livermore National Laboratory, P.O. Box 808, L-482, Livermore, CA, 94551
Captain S. Massey
**United States Air Force, Air Force Research Laboratories, Albuquerque, NM*

Abstract:
OCIS codes:

INTRODUCTION

Thin-disk laser configurations have recently been demonstrated at cw output powers exceeding 1 kW [1]. Thin-disk lasers enable the generation of high average power by minimizing the distance over which waste heat is transported. A disk-laser of transverse dimensions significantly larger than its thickness will sustain laser output with intensity proportional to the thermal flux it dissipates. The fracture strength of the laser material limits the maximum temperature difference of a credible design. Further increases in the heat dissipation capacity of a disk varies inversely with the disk thickness (t) thus, the average laser output intensity of a thin-disk laser scales as 1/t; that is, to maximize the output intensity we must use the thinnest possible disk that is consistent with the pump geometry. The main challenge for the laser designer is then to coerce a thin gain sample into absorbing pump power efficiently. For this purpose, use of a highly absorbing gain medium is desirable in combination with a pumping geometry that allows multi-passing of the pump light. An important feature of the thin-disk laser is that one-dimensional thermal gradients away from the edges are made to align with the extraction beam. Thus, as long as pumping and cooling fields are uniformly distributed, the contributions to wavefront error from dn/dT and the stress optic effect integrate along a 1-dimensional thermal gradient and a constant optical path-length-difference across the extent of the beam. The thin-disk laser therefore, holds promise for high beam quality at high average power.

Professor Adolf Giesen and co-workers at the University of Stuttgart have been leading the development of high power thin-disk lasers. Due to the very short absorption distance, Stuttgart scientists have developed multi-pass pump geometries that accommodate the use of thin disks,

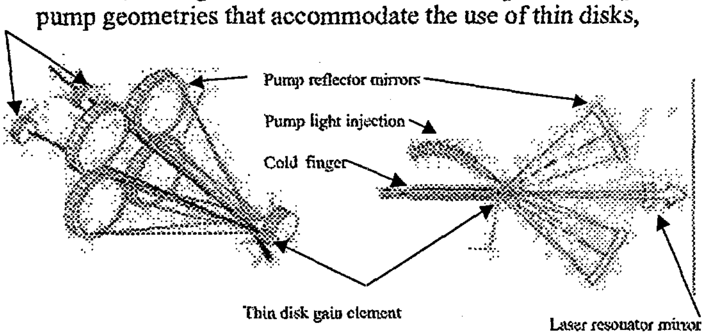


Figure 1. Original thin disk geometry developed by the Stuttgart group in which the pump radiation is re-imaged multiple times onto the thin disk sample to increase absorption length.

Figure 2 shows the original multipass pump geometry employed by the Stuttgart group. Here, the pump beam is re-imaged through the sample more than 16 times to increase the net absorption path. Using this approach Giesen's group obtained 60 watts cw in the fundamental mode from a single Yb:YAG disk. To achieve this high beam quality, the fundamental mode of the resonator was matched with the pump diameter in the thin- disk [1]. More recent versions employ a clever parabolic reflector and porro prisms to simplify the pump geometry. With reduced beam quality, the Stuttgart scientists have produced a record 650 W cw output power from a single crystal with over 50% optical efficiency [2, 3] and over 1 kW with 4 disks in series. The very complicated pump geometry, and the obvious limitations to power scaling that it imposes, are issues that our composite thin-disk explicitly recognizes and addresses.

COMPOSITE THIN-DISK GEOMETRY

With funding from the Joint Technology Office (JTO), we are exploring an alternative configuration by edge-pumping a composite thin-disk laser (Figure 2).

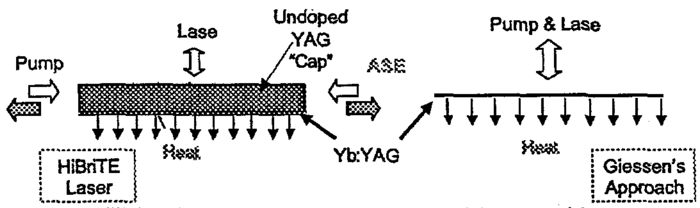


Figure 2. Thin disk lasers having potential for good beam quality at high power can be based on bonding an "undoped cap" on the thin disk element

Figure 2 depicts our enhancement of the composite thin-disk approach, (together with the Geissen's geometry). At the top of the gain-loaded Yb:YAG thin-disk layer there is an index matched undoped cap, attached using diffusion bonding technology. The purpose of the <u>undoped cap</u> is three-fold:

1) With the increased aperture available on the edges, it enables edge pumping of the thin disk, guiding the pump light. The pump geometry is greatly facilitated by edge-pumping the gain sample using non-imaging lens duct technology, in contrast to the complicated re-imaging method of Giesen;
2) Amplified Spontaneous Emission (ASE) as well as parasitic modes are suppressed by more than a factor of >100. The ASE impact is minimized because the optically-passive undoped YAG cap volume adjacent to the Yb:YAG thin gain-sheet drastically reduces the solid angle over which fluorescence is trapped by total internal reflection;

3) The composite thin-disk laser geometry adds strength – in proportion to the cube of its thickness – to the otherwise fragile thin-disk, resisting the effects of thermally induced deformations currently the main source of wave front errors in these devices. Figure 3 shows the result of our thermo-mechanical calculation illustrating this point.

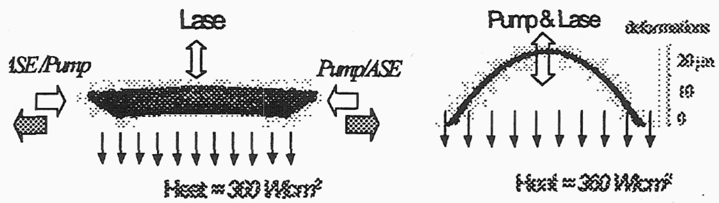


Fig. 3: A two-dimensional thermo-mechanics model we developed was used to compare the deformations of a 200 µm thin-disk laser under identical heat load (at the current design of 360 W/cm²) for the two approaches. The composite thin disk with its diffusion bonded, optically passive "cap" bends 0.8 µm while the "bare" thin-disk bows 23 µm.

Finally, it is crucial to recall that the diffusion bonded undoped cap does not compromise the thermal advantage of the thin Yb:YAG portion. The cap simply rises to a uniform, constant temperature, a benign effect which does not affect the thermal gradients in the thin-disk.

DESIGN CRITERIA IN THE PRESENT DEVICE

The present design emphasizes thermal management predicated on indium soldering the composite gain medium by its thin-film HR mirror to a high performance cooler of mini-channel design. A summary of our approach, accentuating the enabling technologies needed is shown in figure 5.

The hardware incorporates diode array pump delivery on two prismatic edges of a composite disk via non-imaging lens ducts with overall de-magnification of 92:1. The lens ducts were designed using a non-sequential Monte-Carlo ray-trace code that accounted for the experimentally measured divergence characteristics of our diode arrays. The far field of our diode arrays was collected and the Cumulative Distribution Function (CDF) used to weight the random number generator (see fig. 5).

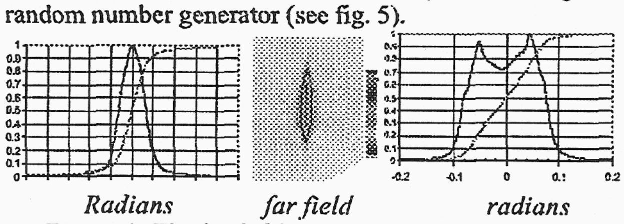


Figure 4. The far field intensity of a 25-bar diode array was imaged using a scientific CCD. Average line-outs in the hori-zontal and vertical axes characterize the diode array divergence. The cumulative distribution functions are also displayed

The precision alignment of the pump delivery hardware –critical to the performance of the device– was easily accomplished by use of metal surfaces that registered each other and a common assembly plate. Thus, all parts were pre-aligned by machined stops before assembly and no adjustments were required. The integrity of our "high value" thin-disk laser gain component is protected by this design. Once soldered to the cooler, it is mated with the lens-duct ends, which utilize a cooler surface for reference. The ensemble is then mated in the assembly plate to the larger pump delivery hardware.

The bottom layer of the composite thin disk is indium soldered to a high performance cooler so, heat is extracted through the thin-film coatings during lasing. In contrast to the method of multiple re-imaging onto the gain medium pursued by the Stuttgart group, the layer of undoped YAG allows the transverse pump to multi-pass the gain medium through TIR analogous to the pumping method in a doubly clad fiber laser. The undoped cap is in intimate contact with the thin gain layer however (nearly) void of thermal sources and insulated elsewhere thus, the steady state temperature must equal the temperature at the diffusion-bonded interface. The thin gain medium develops a thermal gradient identical to that of a cap-less thin-disk and so, the composite laser gain element maintains the thermal advantages of the thin-disk while enabling copious diode power to be injected through the edges, trapping it within and hence multi-passing the gain medium. Secondly, the addition of the relatively thick, optically passive cap greatly reinforces the thin-disk lessening the effects of thermally induced mechanical distortions. By minimizing disk deformations, the isothermal cap helps the thin-disk heat source maintain contact with the cooler. Furthermore, the diffusion-bonded, index-matched cap layer allows fluorescence decay to propagate freely out of the gain medium, while the edges of the composite are cut at a steep angle to effectively reflect the amplified spontaneous emission (ASE) clear away from the gain element.

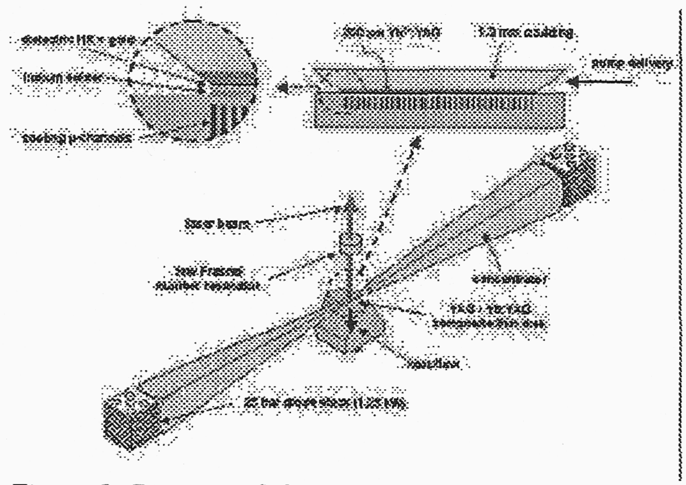


Figure 5. Diagram of the apparatus we are testing. The composite thin-disk design used for this work resembles a narrow light-guide. The thin Yb:YAG gain medium is diffusion bonded to a thicker, index-matched YAG cap enabling edge pumping. The cap also provides mechanical stiffness and ameliorates amplified spontaneous emission effects by diluting fluorescence. For low wavefront distortions, the laser beam is normal to the cooling surface, parallel to thermal gradients in the thin gain medium

RECENT PROGRESS

Considerable progress has been made during the past year. Hardware was designed, built and successfully activated. We made significant advances in all key technology areas. We have obtained and tested several composite thin-disk gain elements such as the one shown on fig. 6, comprising a diffusion-bonded index-matched, undoped layer of YAG 1.3-mm thick to the top of a 200-µm thick Yb:YAG disk doped at 15% Yb (fig. 6).

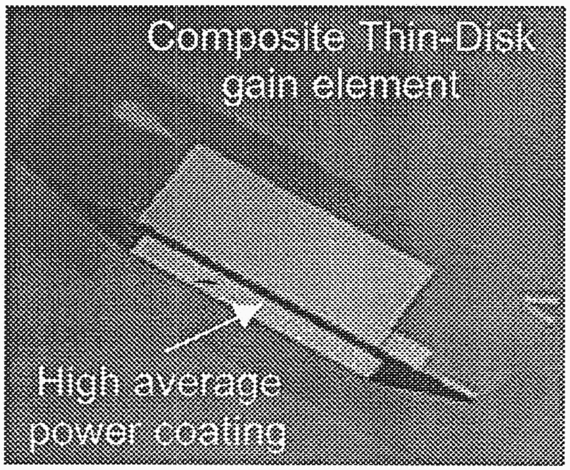


Figure 6. Picture of fully coated, 15%Yb:YAG / YAG composite thin-disk. The composite thin-disk design used for this work resembles a narrow light-guide. The thin Yb:YAG gain medium is diffusion bonded to thcker Nd:YAG material to enable edge pumping, add strength and ASE dilution.

The bottom surface of the laser crystal is coated with dielectric thin films as well as metal for reflecting pump light and serve as the cavity mirror. A suitable HR coating on on the Yb:YAG/YAG composite gain element has been developed after many iterations to meet the demands placed on the thin film by the unusual optical architecture: 1) reflect the 1030nm laser wavelength with high efficiency(>99.8% @ 1030nm), 2) reflect diode pump light at 940nm over a broad phase space, 3) conduct a heat flux of

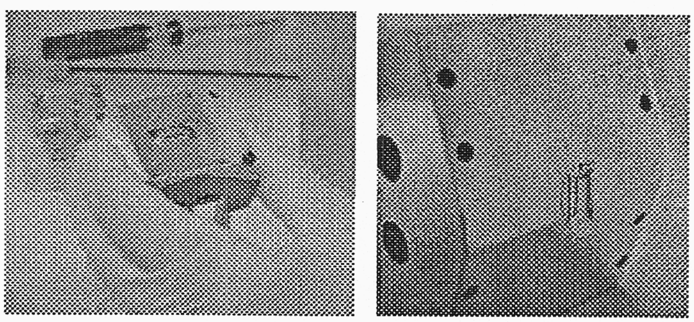
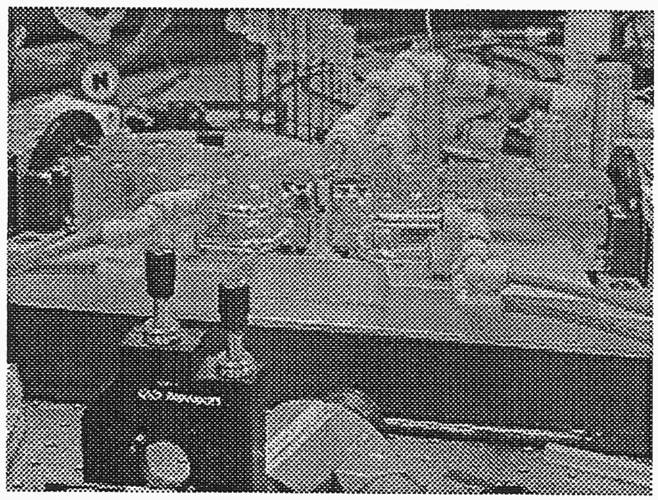


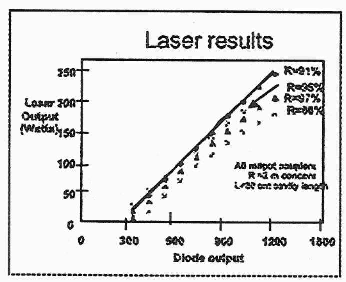
Figure 7: A fully coated thin-disk on the left is fixtured to the cooler prepare it ndium soldering fixture and after soldering to the cooler

360 W/cm^2, and 4) compatibility with indium solder. We developed a thin-film coating that meets these specifications consisting of: 1) 11 layer pair of Ta2O5 / SiO2 sputtered onto the Yb:YAG crystal as the laser wavelength high reflective coating, 2) Plasma etch in Oxygen, 3) ½ wave of Al_2O_5 as an adhesive layer, 4) Plasma etch in oxygen, 5) 300nm of Cu sputtering as a broadband reflector, 6) 1000nm of Ni as a metal film barrier to prevent indium migration during soldering, 7) 300nm of Au as a solder agent for Indium, and 8) ~10 µm of evaporated Indium solder to attach to high performance cooler. We chose a mini-channel cooler design made out of Cu-W (15% Cu, 85% W) to match the thermal expansion properties of the YAG. The cooler was constructed by wire EDM cutting 125 µm channels with 250 µm separation and 3 mm in length. Electroplated gold coatings were used to reflect the pump light.

Tha Hardware was successfully activated in "first light" experiments in December of 2001. A picture of this hardware in the experimental set up is shown in the LHS of Fig. 6. During initial operation at low duty factor (1 ms pulses at 1 to 10 Hz) a stable, multi-mode resonator was used to collect slope efficiency data (laser output vs. input energy) for several concave (R = 2 m) output couplers. The output power optimized with the 91% reflector (see the graph in Fig. 8b).. These data were compared with our energetics codes predictions. Agrement between the model and the data was found for a the average temperature of 380 K.



a)



b)

,Figure 8. a) The hardware was activated successfully in December of 2001 in low duty factor experiments. .b) Efficiency of 20 % with respect to the diode output was obtained. The data matched our energetic model at temperature of 380 K.

AKNOWLEDGEMENTS

The authors wish to thank K. Kanz, J. Lang, P. Thelin, G. Loomis, S. Mills and Lorraine DiMercurio), all with the Lawrence Livermore National Laboratory, for their assistance. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.
L. E. Zapata's e-mail address is zapata1@llnl.gov.

References

1. A. Giesen, H. Hugel, A. Voss, K. Wittig, U. Brauch, H. Opower, "Scalable concept for diode-pumped high-power solid-state lasers," Appl. Phys. B 58, 365-372 (1994).

2. C. Stewen, K. Contag, M. Larionov, A. Giesen, H. Hugel, "A 1-kW CW Thin Disc Laser," IEEE Journal Of Selected Topics In Quantum Electronics 2000, 6, 650-657. (2000).

3. M. Karszewski, S. Erhard, T. Rupp, A. Giesen, "Efficient high-power TEMoo mode operation of diode-pumped Yb:YAG thin-disk lasers," in Adv. Lasers Solid-State Meeting Tech. Dig., Dovos, Switzerland, Feb. 13-16, pp. 13-15, (2000).

4. R. J. Beach, "Theory and Optimization of Lens Ducts," Applied Optics, 35, pp. 2005-2015, (1996).

5. R. J. Beach, "CW theory of quasi-three level end-pumped laser oscillators," Optics Communications 123, pp 385-393, (1995).

6. T. Y. Fan, IEEE J Quantum Electron, 29, pp. 1457-1459, (1993).

7. D. C. Hanna, C. G. Sawyers, M. A. Yuratich, "Telescopic Resonators for Large-Volume TEMoo-Mode Operation," Opt Quantum Electron. 13, 493 (1981).